ANALYSIS OF A PULSED POWER SYSTEM CONTAINING ROTATING MACHINE*

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Abstract

Several hundred megajoules of energy lasting for several seconds are required for magnetic fusion experiments. Such high energy can be stored as inertial energy in an alternator which is brought up to speed slowly. The alternator is then discharged through a thyristor converter to magnets which produce and sustain the plasma. A major portion of the inertial stored energy, for reversed field pinch experiments in Los Alamos, will be dissipated in charging the magnetizing coil to produce the plasma. The plasma is then sustained, during the flat-top period, by energizing the magnetizing coil in the reverse direction. To hold the plasma current constant at the required level, the output voltage of the converter must be held at a prescribed level by controlling the firing angle of the thyristors. The paper discusses the possibility of using the same converter for both the magnetizing and the flat-top periods. It also analyzes the electrical requirements that will be imposed on the alternator and the converter.

Introduction

The poloidal- and toroidal-field circuits of the proposed Los Alamos reversed-field pinch experiments in magnetic fusion will require four types of power supplies: three for the poloidal fields and one for the toroidal field. Of the many design variations being considered now, the paper discusses the magnetizing and the flat-top power supplies of one design concept. A simplified schematic of the poloidal-field circuit is shown in Fig. 1.

To eliminate disturbances to electrical loads in the Los Alamos area, the pulse-power system for the proposed reversed-field-pinch experiment will be fed by a motor-generator set. The ac power of the generator will be converted to dc by converters which will consist of thyristor-controlled bridges. The magnetizing and the flat-top power supplies will have modular design, each module consisting of four bridges connected in parallel. These modules, in turn, will be connectd in series or in parallel to provide the required power.

The experimental procedure is as follows:

1. The alternator is brought up to speed, for instance, by an induction motor which is connected to the 13.8-kV electric utility distribution system.

2. Once the alternator has been brought up to speed, and excited with the predetermined field current, it is connected to the magnetizing winding through the converter to initiate the magnetizing period.

3. Once the current has reached the required value, the alternator is disconnected from the magnetizing power supply, and the vacuum circuit breakers are opened to produce high voltage in the magnetizing winding to establish the plasma.

4. The alternator is then connected to the flat-top power supply which passes current through the magnetizing winding in the opposite direction to initiate the flat-top period. To hold the plasma
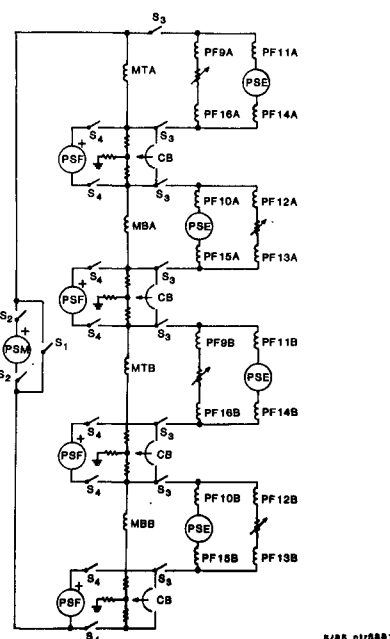
Fig. 1 Simplified schematic of poloidal field circuit. At the end of magnetizing period (t = 0), S1 closes, S2 opens, S3 closes and CB opens. At the beginning of flat-top period (t = 20 to 40 ms), S4 closes. PSM, PSF are magnetizing and flat-top power supplies. MTA, MBA, MTB and MBB are four sections of the magnetizing winding.

current constant (flat top), the output voltage of the converter must supply the plasma voltage drop.

The electrical requirement during the magnetizing period is that the current through the resistive-inductive load must reach 68 kA in as short an interval as possible consistent with the power supply rating to minimize energy loss and heating. Therefore, the dc output voltage of the magnetizing power supply should be as high as possible. The thyristor valves are, therefore, fully switched on during the magnetizing period. On the other hand, the current during the flat-top operation must supply the plasma voltage drop, to hold the plasma current constant. Therefore, the output voltage of the flat-top power supply must be regulated by the control of the thyristor firing angle while the alternator voltage decreases with its speed as its kinetic energy is transformed into electrical energy to its loads.

Combined Magnetizing and Flat-Top Power Supplies

The flat-top power supply is connected to the poloidal-field circuit approximately 20-40 ms after the magnetizing power supply is disconnected. Therefore, it may be advantageous to use the same power supply during both the magnetizing and the flat-top periods. A scheme to perform both the functions with the same power supply is shown in Fig. 2.

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14. ABSTRACT
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MAGNETIZING POWER   FLAT-TOP POWER   SWITCHING FOR MAGNETIZING POWER

SWITCHING FOR FLAT-TOP POWER

COMBINED POWER SUPPLY FOR MAGNETIZING
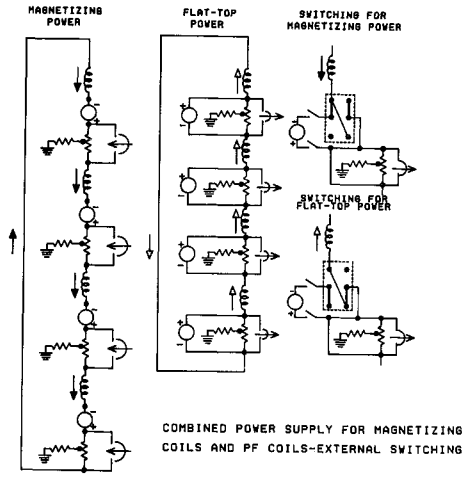COILS AND PF COILS-EXTERNAL SWITCHING

Fig. 2 Combined power supply for magnetizing and flat-top periods: External switching.

Each of the four sections of the flat-top power supply is composed of three modules, each module comprising four three-phase, full-wave thyristor bridges connected in parallel. During charging of the magnetizing winding, the three modules are connected in parallel; they are connected in series during flat-top operation. The external connection for the changeover is performed by two disconnect switches: a single-pole, single-throw switch and a double-pole, double-throw switch for each of the four sections. The intermodular connection for series/parallel operation is performed by two double-pole, double-throw disconnect switches. The thyristors will be blocked during the operation of these disconnect switches so that no power will be interrupted by these switches.

Analysis of the Magnetizing Period

Modeling of Generator

Initially the energy is stored entirely in the rotational inertia of the generator, its no-load losses being supplied through its prime mover by the power drawn from the electric utility system. Once the load is connected to the generator, both its speed (and frequency) and terminal voltage will decrease. The speed decreases because part of the inertial stored energy is converted into electrical energy during the experiment; the available voltage to the load decreases partly because of the decrease in generator speed and partly because of the voltage drop internal to the generator.

If the magnetizing period is divided into small time steps, ts, then

$$dq = -(pn + v \cdot i) \cdot ts,$$

$$q(t2) = q(t1) + dq, \text{ and} \qquad (1)$$

$$f(t2) = f_0 \sqrt{q(t2)/qo},$$

where pn = no-load losses of the generator, v, i = dc load voltage and current during ts, $q(t1)$, $q(t2)$ = generator inertial energy at t_1 and t_2, $f(t2)$ = generator frequency at t2, and f_0, q_0 = initial frequency and

stored energy of generator. The dc load current at t2 can be calculated from

$$di = (v - r \cdot i) \cdot ts/\ell; \quad i(t2) = i(t1) + di, \qquad (2)$$

where r, ℓ = load resistance and inductance and i(0) = 0. The calculation of the dc load voltage v requires the knowledge of the electrical characteristics of the generator and of the converter. This will be discussed later.

The electrical characteristics of the generator were derived in accordance with Park's theory [1]. The generator internal voltage can be computed once its field current and speed are known. The generator terminal voltage is computed by substracting the various impedance drops, internal to the generator. Figure 3 shows the phasor diagram of the generator voltages.
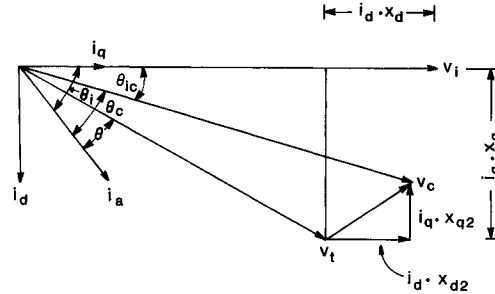

Fig. 3 Phasor diagram of generator voltages.

The voltage vc in Fig. 3 is the voltage behind the "commutating" reactance. The commutating reactance is defined as that reactance per phase during the interval current is transferring from one rectifier leg to another. During this short interval, the subtransient reactances of the generator are significant. Therefore, the voltage drop across these reactances vdq2 is vectorially added to the generator terminal voltage vt to determine vc, e.g.,

$$vdq2 = id \cdot xd2 + j \cdot iq \cdot xq2$$

$$= ia \cdot \sqrt{(xd2 \cdot \sin\theta \, i)^2 + (xq2 \cdot \cos\theta \, i)^2} \qquad (3)$$

$$= ia \cdot xcg,$$

where xd2, xq2 are the subtransient direct- and quadrature-axis reactances of the generator, and xcg is the commutating reactance of the generator.

It is known that on sudden short circuit or sudden application of load to a generator, the internal reactances of the generator change from low values at the beginning of the period to higher steady-state values at the end of the period. To accommodate such change in the generator reactances, equivalent direct- and quadrature-axis reactances were assumed, which are given by

$$1/xde = (1/\omega) \cdot [(1/\ell d) + \{(1/\ell d1) - (1/\ell d)\} \cdot t1 \\ + \{(1/\ell d2) - (1/\ell d1)\} \cdot t2], \qquad (4a)$$

$$1/xqe = (1/\omega) \cdot [(1/\ell q) + \{(1/\ell q1) - (1/\ell q)\} \cdot t3 \\ + \{(1/\ell q2) - (1/\ell q1)\} \cdot t4],$$

$$t1 = \exp(-t/td1); \quad t2 = \exp(-t/td2),$$

$$t3 = \exp(-t/tq1); \quad t4 = \exp(-t/tq2), \tag{4b}$$

where $\ell d, \ell q$ = direct- and quadrature-axis synchronous inductances,
$\ell d1, \ell q1$ = direct- and quadrature-axis transient inductances,
$\ell d2, \ell q2$ = direct- and quadrature-axis subtransient inductances,
$td1, tq1$ = direct- and quadrature-axis transient time constants, and
$td2, tq2$ = direct- and quadrature-axis subtransient time constants.

Modeling of Load and Converter

The load is the magnetizing winding which consists of a resistance and an inductance, connected in series. Electrically, a continuously decreasing dc voltage (converter output) charges an RL-circuit exponentially to a specified current level.

A 12-pulse converter consists of a bank of three-winding wye/wye/delta transformer and two three-phase full-wave thyristor bridges, each connected to one of the two secondaries of the transformer. The analysis will be the same if the three-winding transformer is replaced by two wye/wye and wye/delta transformers.

The thyristors in the converter conduct fully, i.e., the firing angle is zero during the magnetizing period. The modeling of converter closely follows the theory of conversion [2], with some modifications. As a 12-pulse converter was assumed, the ac line current i_a is given by [2], [3]

$$ia = (2\sqrt{6}/\pi) \cdot i \cdot \left[\frac{1 + \cos\delta}{2 \cdot \eta \cdot \cos\theta\, i}\right], \tag{5}$$

where i = dc load current,
δ = arccos $(1 - i/is)$
is = 0.1949. $vc/(f \cdot \ell c)$,
ℓc = commutating inductance of the ac system,
θi = arctan $\{(2\delta - \sin 2\delta)/(1 - \cos 2\delta)\}$, and
η = converter efficiency.

A second modification, because of the 12-pulse conversion, is that the commutating reactance of the generator seen from the converter is half of the generator actual commutating reactance [4], i.e.

$$xc = (xcg/2) + xt, \tag{6}$$

where xc is the total commutating reactance of the system, and xt is the transformer commutating reactance.

The voltage behind the commutating reactance vc and the dc load voltage v are determined iteratively at each time step ts, starting from their initial values at no load for $t = 0$, as follows:

$$vco = vg/nm \cdot \sqrt{3}; \quad vo = 3\sqrt{2} \cdot vg/\pi \cdot nm, \tag{7}$$

where vg is the generator line-to-line rms voltage at no load, and nm is the voltage transformation ratio of converter transformer for the magnetizing period.

The various voltage phasors and their corresponding angles of Fig. 3 can be constructed, by trigonometric manipulations, at each time step, starting with the initial values of vc and v (eq. 7) and $i(t=0) = 0$, θic $(t=0) = 0$, remembering that the generator internal voltage vi is reduced at each time step in proportion to its frequency, i.e.,

$$vi = (f/fo) \cdot (vg/nm \cdot \sqrt{3}) \tag{8}$$

Analysis of the Flat-Top Period

Once the magnetizing coils are charged to the required current, the generator with the converter is disconnected from the load, and the vacuum circuit breakers CB (Fig. 1) are opened to initiate the plasma. Once the plasma is formed, energy must be supplied to the magnetizing coil to compensate for the losses in the plasma resistance, to keep the plasma current constant. The converter output voltage must equal the plasma voltage drop to keep the plasma current constant. The firing angle of the thyristors in the converter must be varied to accomplish this.

The generator model is the same as for the magnetizing period. However, the models for the load and the converter are different from those for the magnetizing period.

Modeling of Load and Converter

The simplified schematic of the load is shown in Fig. 4. The following are specified: 1. the load voltage v, and 2. the plasma current ip, e.g.,

$$v = ip \cdot rp \cdot nmc, \text{ and} \tag{9}$$

$$ip = ipo$$

where ipo = initial plasma current, and nmc = number of turns of the magnetizing coil. The converter output current i is found by analyzing Fig. 4,

$$i = (ipo/nmc) \cdot [\exp(-a_2 \cdot t) - \exp(-a_1 \cdot t)] + (v/nmc^2 \cdot r1) \cdot$$

$$[1 - \exp(-a_1 \cdot t)] + (v/nmc^2 \cdot rp)[1 - \exp(-a_2 \cdot t)], \tag{10}$$

where, $a_1 = r1/\ell 1$, and $a_2 = rp/\ell p$.

Several "fictitous" terms are then defined in order to determine the required firing angle of the thyristors in the converters [2].

$$vo = 2.3391 \cdot vc$$

$$is = vo/(12 \cdot f \cdot lcf); \quad c = i/is \tag{11}$$

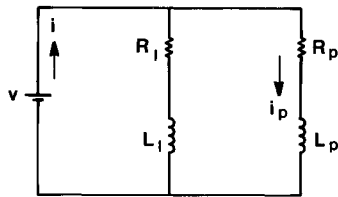$$b = v/vo; \quad b1 = b + 0.5 \cdot c; \quad b2 = b - 0.5 \cdot c$$

Fig. 4 Simplified schematic of load during flat-top period. R_p, L_p = plasma resistance and inductance.

where vc = voltage behind the commutating inductance, and ℓcf = commutating inductance in the flat-top period. From eq.(11), the firing angle α, and the overlap angle u can be determined,

$$\alpha = \text{arcccos (b1)}; \quad u = \text{arccos (b2)} - \alpha \qquad (12)$$

The computation of the voltage behind the commutating reactance vc, and the converter output (active and reactive powers) is similar to that for the magnetizing period.
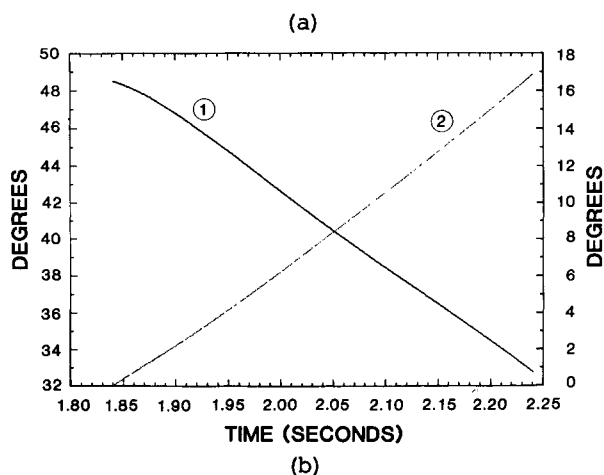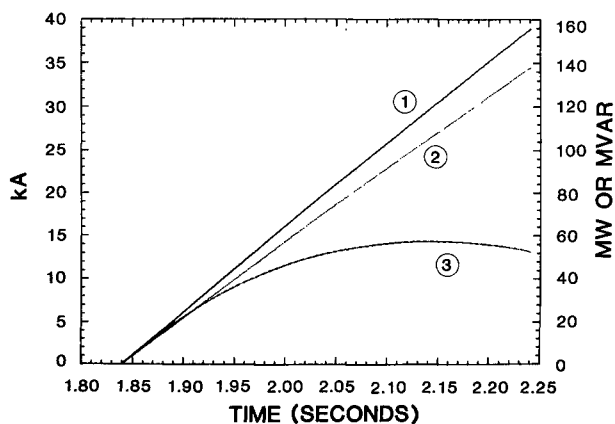

(a)

TIME (SECONDS)

(b)

Fig. 5 Profiles of variables during flat-top period.
(a) 1. converter output current, 2. converter power, 3. converter reactive power.
(b) 1. converter firing angle, 2. overlap angle.

Figure 5 shows the profiles of some of the variables during the flat-top period.

Discussion

Generally, the commutating reactance of a synchronous machine is assumed to be either the arithmetic or the geometric mean of xd2 and xq2. This is not correct. The effects of armature reaction on the generator field flux are twofolds: 1. the direct-axis component of armature current demagnetizes the field flux, and 2. the quadrature-axis component cross-magnetizes the field flux. The resultant effect of armature reaction is a voltage drop internal to the machine. As the demagnetizing and the cross-magnetizing effects of armature current are at quadrature to each other, the two components of internal voltage drop must also be at quadrature to each other. Therefore, xcg of Eq. (3) should be the correct form of the synchronous-machine commutating reactance.

Once the load characteristics are known, the pulsed power system can be optimized with the help of the proposed analysis. For instance, the reactive power requirement can be minimized by proper choice of series/parallel combination of the converter modules and the voltage ratio of the converter transformers. Whether the plasma current is held constant during the flat-top period for a specific choice of the power supplies can also be easily ascertained.

Conclusions

1. A new concept for the synchronous-machine commutating reactance is presented.

2. A simple and fast but accurate method of analysis is developed to design a pulsed power system containing a rotating machine.

3. The use of the same power supply for both the magnetizing and the flat-top periods is economically attractive, and technically feasible, particularly because the changeover switches do not have to interrupt power.

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